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A Steady-State Heat Meter for Determining the Heat-Transfer Rate to a Cooled Surface

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JET PROPULSION LABORATORY
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E. A. Laumann

Robert E. Covey

Robert E. Covey, Chief
Aerodynamic Facilities Section

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ABSTRACT

The design of a steady-state heat meter is presented. The meter is intended to operate in the heating-rate range between 0.1 and 2.0 Btu/ft^2-sec. It uses Teflon as the primary meter material, thus creating a maximum temperature limit of 450°F. The suggestion is made that the substitution of a material other than Teflon would extend this temperature limit. The results of experimental work using heat meters of this design are given.

I. INTRODUCTION

During the course of development of a transient technique for determining aerodynamic heating on models in the JPL hypersonic wind tunnel (see Ref. 1), it became evident that there existed a heating-rate threshold. This threshold represented a line of demarcation below which no acceptable data could be obtained because of the physical limitation of the material and equipment available. This Report describes a device which was developed to circumvent rather than eliminate the physical limitations of the transient technique.

The steady-state heat meter described here was developed principally for making aerodynamic heating measurements in the hypersonic tunnel. However, minor modifications would permit its use in innumerable scientific and industrial applications.

II. THEORY

A. Philosophy

The intent was to design a device within the state-of-the-art which would measure low heating rates. Exotic subsidiary electronics equipment was considered undesirable. The combination of a steady-state technique and thermocouple sensors appeared to provide the most direct approach. To obtain significant thermal resolution, a material of low thermal conductivity and relatively wide thermocouple spacing was dictated. To provide some degree of directionality to the heat flow through the material, a thermal insulator was needed.

From these criteria, the heat meter shown in Fig. 1 was evolved. The meter is made of DuPont Teflon (see Ref. 2), the insulation of DuPont Tipersul (see Ref. 3), and the heat sink of aluminum, with chromel-constantan thermocouples used as the sensors. Teflon was selected because of its low thermal conductivity, high dielectric strength, relatively high useful temperature limit, and machinability. Tipersul was used because of its excellent insulation qualities. Aluminum was used because of its high thermal diffusivity. Chromel-constantan thermocouples were used because of the high signal-to-temperature ratio.

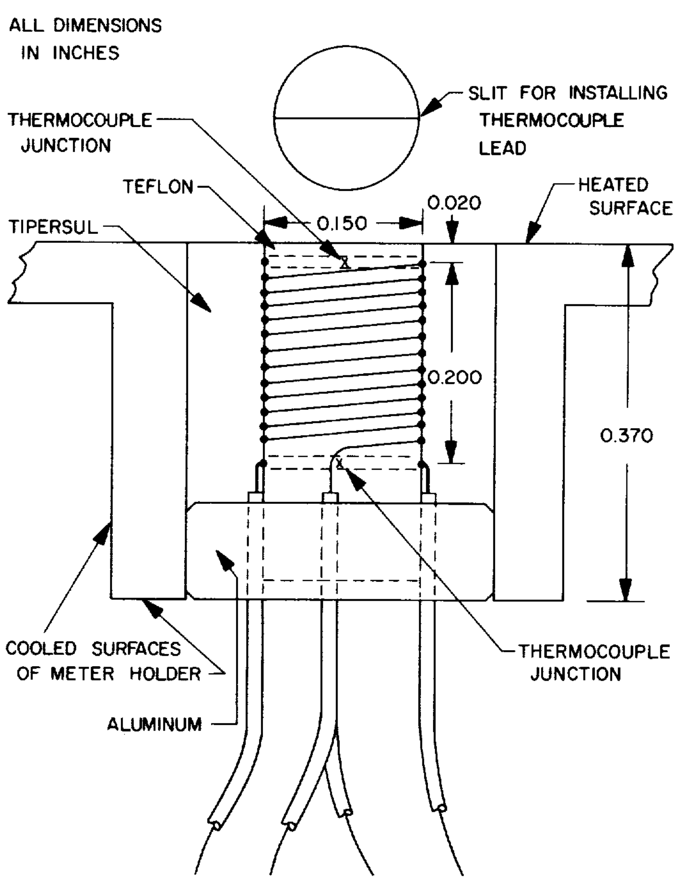

Fig. 1. Steady-state heat-meter schematic

B. Thermocouple Lead Error Reduction

To prevent the thermocouple leads from draining excess heat from the upper part of the meter and thus reducing the temperature at the junction, the spiral-wrap method of thermocouple lead routing was devised. The intent was to reduce the heat flowing through the leads to an acceptable minimum with respect to the heat flowing through the Teflon. This was accomplished as follows:[1]

$$\dot{Q}_{TE} = (k_{TE}/L_{TE})\, A_{TE}\, (T_o - T_i)_{TE}$$

$$\dot{Q}_{TC} = (k_{TC}/L_{TC})\, A_{TC}\, (T_o - T_i)_{TC}$$

Because the leads are in direct contact with the Teflon, their temperatures are the same at any point; therefore,

$$(T_o - T_i)_{TE} = (T_o - T_i)_{TC}$$

and

$$(\dot{Q}_{TC}/\dot{Q}_{TE}) = (k_{TC}\, L_{TE}\, A_{TC})/(k_{TE}\, L_{TC}\, A_{TE})$$

but

$$A_{TE} = \pi/4\, (d_{TE})^2$$

$$A_{TC} = 2\,\pi/4\, (d_{TC})^2$$

The 2 enters the A_{TC} equation because there are two thermocouple leads.

Then

$$L_{TC} = N\, \{[(L_{TE})^2/N] + \pi^2\, (d_{TE})^2\}^{\frac{1}{2}}$$

[1]See Nomenclature for a definition of terms.

and

$$\frac{\dot{Q}_{TC}}{\dot{Q}_{TE}} = \frac{2\, k_{TC}\, L_{TE}\, (d_{TC})^2}{k_{TE}\, N\, \{[(L_{TE})^2/N] + \pi^2\, (d_{TE})^2\}^{\frac{1}{2}}\, (d_{TE})^2}$$

From the above equation the desirability of small diameter thermocouple leads and a large number of turns are self-evident.

A maximum limit of N exists in that the two different types of wire must not touch as they spiral down the Teflon shank; thus,

$$N < L_{TE}/2d_{TC}$$

C. Meter Heat Balance and the Theoretical Calibration Factor

In order to make the heat meter a useful tool, the internal heat balance must be determined. That is, the amount of heat flowing through the heat meter face must be correlated with the resulting temperatures at the two thermocouple locations.

A problem similar to the present one is presented in Section 11-5 of Ref. 4. The solution of Ref. 4 can be used, provided certain terms are re-defined.

$$\dot{q}_o = [(4\, k_{TE}\, H)/(d_{TE})]^{\frac{1}{2}}\, \frac{1 - p \exp(-2\, m\, L'_{TE})}{1 + p \exp(-2\, m\, L'_{TE})}\, \theta_o$$

(Ref. 4, Eq. 11-30)

$$p = (k_{TE} m - H^*)/(k_{TE} m + H^*)$$

$$m = \{(4\, H)/[k_{TE}\, (d_{TE})]\}^{\frac{1}{2}}$$

$$H^* = k_{TE}/(L'_{TE} - L_{TE})$$

$$\dot{q}'_o = (k_{TE}/L_{TE})\, \theta'_o$$

Then

$$\frac{\dot{q}_o}{\dot{q}'_o} = m\, L_{TE}\, \frac{1 - p \exp(-2\, m\, L'_{TE})}{1 + p \exp(-2\, m\, L'_{TE})}\, \frac{\theta_o}{\theta'_o}$$

but

$$\theta'_o = \theta_o - \theta_i$$

and

$$\frac{\theta_i}{\theta_o} = \frac{\exp(-m\, L_{TE}) + p \exp[-m\, (L_{TE} - 2\, L'_{TE})]}{1 + p \exp(-2\, m\, L'_{TE})}$$

(Ref. 4, Eq. 11-26)

so

$$\frac{\theta_o}{\theta'_o} = \frac{1}{1 - (\theta_i/\theta_o)}$$

$$\frac{\theta_o}{\theta'_o} = \frac{1 + p \exp(-2\, m\, L'_{TE})}{1 - \exp(-m\, L_{TE}) + p\, \{\exp(-2\, m\, L'_{TE}) - \exp[-m\, (2\, L'_{TE} - L_{TE})]\}}$$

and

$$\frac{\dot{q}_o}{\dot{q}'_o} = m\, L_{TE}\, \frac{1 - p \exp(-2\, m\, L'_{TE})}{1 - \exp(-m\, L_{TE}) + p\, \{\exp(-2\, m\, L'_{TE}) - \exp[-m\, (2\, L'_{TE} - L_{TE})]\}}$$

By definition,

$$H = k_{Ti}/X^*$$

$$X^* = (d_{TE}/2) \ln (d_{Ti}/d_{TE})$$

(Ref. 5, Eq. 2-9)

Though temperature does not appear in the above equation, the ratio is temperature-sensitive to the extent that the thermal conductivities of the Teflon and Tipersul are temperature-dependent.

III. APPLICATION

The primary purpose of the Teflon-Tipersul heat meter developed from the theory was to measure heating rates in the range of 0.1 to 2.0 Btu/ft²-sec. The lower limit represented the minimum heating rates expected from aerodynamic heating in the hypersonic tunnel. The upper limit represented approximately the lower limit of the capabilities of the JPL transient heat-transfer technique.

The design presents several limitations. The meter has a maximum continuous operating temperature of 350°F and a maximum short term operating temperature of 450°F because of the decomposition characteristics of Teflon at elevated temperatures. The meter requires a heat pump to extract heat from the base so that it may operate in a steady-state condition. On the occasions that the meter has been used thus far, a jet of cold nitrogen gas, directed on the base of the meter, has served as an adequate heat pump.

To determine the heating rate to a surface other than that of the heat meter, the heat-transfer coefficient must be determined as:

$$h = \dot{q}_o/(T_a - T_o)$$

Then the heating rate to any other surface in the same environment can be determined by the following equation:

$$\dot{q}_s = h\,(T_a - T_s)$$

IV. EXPERIMENTS

Two heat meters were used to measure the aerodynamic heating on the cylindrical portion of a hemisphere-cylinder model tested in the JPL hypersonic wind tunnel at Mach numbers 5 and 8½. The tests of these heat meters were run in conjunction with some transient heat-transfer tests reported in Ref. 1.

The meters were installed in the thin-walled model (see Fig. 2) by means of mild-steel tubular adaptors. A manifold inside the model directed a jet of cool nitrogen gas onto the base of each of the heat meters, the surrounding adaptors, and model walls.

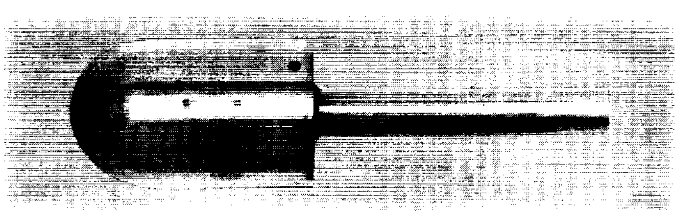

Fig. 2. Heat meters installed in model

To obtain useful aerodynamic heating data from the heat meters, the coolant gas pressure was adjusted until the heat-transfer rate from the meter bases created significant temperature differences at the two thermocouple locations. When steady-state conditions existed at the two thermocouple locations, the thermocouple output signals were recorded.

From these data, the aerodynamic heat-transfer rate was determined as follows:

$$\dot{q}_o = [(\dot{q}_o/\dot{q}_o^{\prime})\,(k_{TE}/L_{TE})]\,(T_o - T_i)$$

The term $[(\dot{q}_o/\dot{q}_o^{\prime})(k_{TE}/L_{TE})]$ is considered a function of the average temperature of the meter. The variation of k_{TE} with temperature was obtained from Ref. 6. Figure 3 shows the variation of $[(\dot{q}_o/\dot{q}_o^{\prime})(k_{TE}/L_{TE})]$ with $[(T_o + T_i)/2]$. These data were then compared with theory as presented in Ref. 1. The comparisons are presented in Fig. 4.

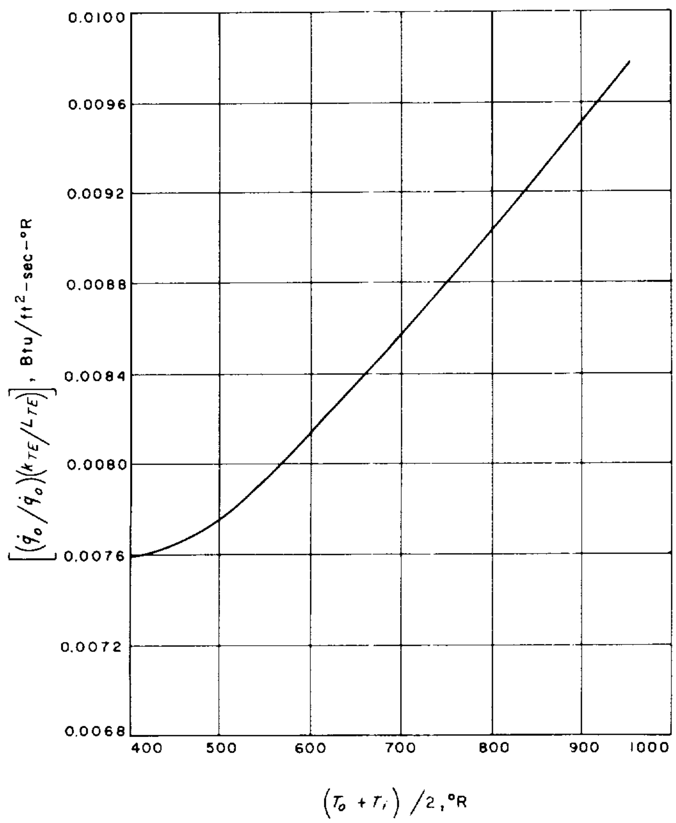

Fig. 3. Theoretical calibration curve of meter

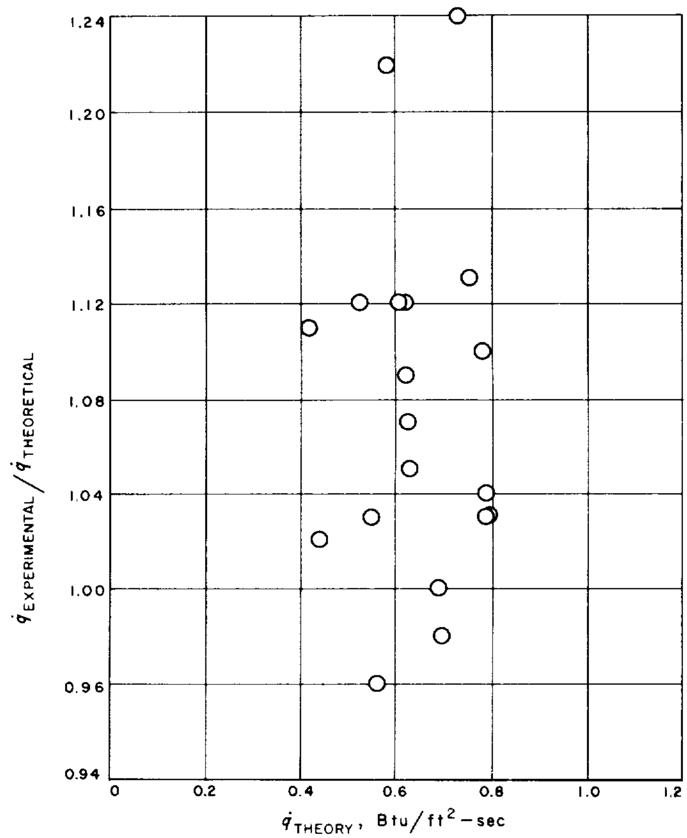

Fig. 4. Experimental results

V. CONCLUSIONS

The heat meters were designed specifically as aerodynamic heating-sensor elements within the heating rate range of 0.1 to 2.0 Btu/ft^2-sec. From the experimental work done thus far, it appears that the meters can be used to measure heating rates to within $\pm 10\%$ of the true value.

There are two primary restrictions within which the meters must operate. First, the meter must be installed in a cooled environment; that is, the theory given in Section II assumes that the temperature at the outer edge of the insulation is the same as the temperature of the meter base. The second restriction is that the maximum allowable temperature of the Teflon should not be exceeded.

There appears to be no need to restrict the meters to wind tunnel usage only. They should be able to measure conductive as well as convective heating from any working fluids. Further, were the Teflon replaced by a ceramic material, the temperature restrictions might be removed.

NOMENCLATURE

- A_{TE} cross-sectional area of Teflon rod
- A_{TC} cross-sectional area of thermocouple wire
- d_{TE} diameter of Teflon rod
- d_{TI} outside diameter of Tipersul insulation
- d_{TC} diameter of thermocouple wires
- H conductive heat-transfer coefficient of insulator
- h convective (aerodynamic) heat-transfer coefficient
- k_{TE} thermal conductivity coefficient of Teflon
- k_{TI} thermal conductivity coefficient of Tipersul
- k_{TC} average of thermal conductivity coefficients of chromel and constantan
- L_{TE} distance between two thermocouples
- L'_{TE} effective length of Teflon rod
- M Mach number
- N number of turns of upper thermocouple lead in length L_{TE}
- $\dot{Q}_{TE}$ total heat flow through Teflon between the upper and lower thermocouple locations
- $\dot{Q}_{TC}$ total heat flow through thermocouple leads between the upper and lower thermocouple locations
- $\dot{q}_s$ heating rate to arbitrary surface
- $\dot{q}_o$ heating rate at upper surface of heat meter
- $\dot{q}_o'$ apparent heating rate at upper surface of heat meter
- T_a temperature of fluid at wall
- T_e temperature at heat meter base and outer edge of insulation
- T_o temperature at upper thermocouple location
- T_i temperature at lower thermocouple location
- T_s temperature of surface of wall
- θ_o $T_o - T_e$
- θ_i $T_i - T_e$

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